

APPLICATION

OF

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FOR

UNITED STATES LETTERS PATENT

ON

SWITCHED NOISE FILTER CIRCUIT FOR A DC-DC CONVERTER

Docket No. A8SJ2550US

Assigned to:

ANALOG DEVICES, INC.

SWITCHED NOISE FILTER CIRCUIT FOR A DC-DC CONVERTER

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to the field of DC-DC converters, and particularly to methods of mitigating the adverse effects of electromagnetic noise sources on such converters.

Description of the Related Art

An important class of DC-DC converter uses the instantaneous output voltage to establish the duty ratio required for maintaining a regulated output. This class includes: 1) converters which do not employ a voltage-error amplifier, e.g., the various valley-voltage and peak-voltage regulators, and the hysteretic regulator; and 2) converters that employ the "Vsquare" technique (described, for example, in U.S. Patent No. 5,770,940).

An example of such a converter is shown in FIG. 1. A switching element 10 is connected between an input voltage V_{in} and a node 12, and an inductor L is connected between node 12 and an output terminal 14 at which a regulated output voltage V_{out} is provided. Switching element 10 is turned on and off periodically. When switching element 10 is closed, $(V_{in} - V_{out})$ is connected across inductor L , such that the current in L (I_L) increases. When switching element 10 is open, I_L continues flowing in rectifier diode D , with I_L decreasing due to the voltage $(-V_{out})$ applied across L . This results in I_L having a sequence of rising and falling segments; i.e., essentially a dc current with a superimposed triangular ripple current. Inductor current I_L feeds a load network comprising a capacitance C_{out} and a load 16. C_{out} is selected to have an impedance at the switching frequency that is much less than that of load 16.

As such, the ripple component of I_L flows mostly in C_{out} , and the dc component flows in the inductor; however, a small ripple voltage component will be present in V_{out} due to I_L 's ripple current component.

5 The switching of element 10 is controlled by a switching control circuit 18, which cycles element 10 on and off once per switching cycle. The common characteristic of converters which use the instantaneous output voltage to establish duty ratio is that a feedback voltage V_{fb}
10 representative of V_{out} - typically produced at a feedback node 20 using a resistive divider (R_1 and R_2) connected between output terminal 14 and the converter's local ground - is connected directly to one of the inputs of a comparator A1. When V_{fb} drops below and/or rises above a
15 reference voltage V_{ref} applied at the comparator's other input, the comparator changes state. Depending on the particular regulation technique employed, this change in state is used to affect the "on" time interval, the "off" time interval, or both the "on" and "off" time intervals of
20 the switching cycle. For example, the regulator in FIG. 1 employs constant-on-time valley-voltage control. A monostable multivibrator (MMV) 22 is triggered when V_{fb} falls below V_{ref} , which toggles the MMV's Q output and closes switching element 10 for a fixed (constant) time
25 interval.

 These converters are often operated in the immediate vicinity of electromagnetic interference (EMI) noise sources, such as other DC-DC converters. Another switching converter can emit a quickly-varying magnetic field, which
30 can be coupled (via mutual inductance) into feedback voltage V_{fb} as noise. In addition, noise of electrical origin - such as the quickly-changing voltage at the switched node of a converter - can be coupled to feedback node 20 via stray capacitance. Noise in the feedback
35 voltage can lead to jitter, undesirable frequency

synchronizations, premature switching, or other malfunctions.

One prior art solution to this problem (shown in FIG. 1) is to add a filter capacitor C_f between feedback node 20 and ground. The capacitor together with divider resistors R1 and R2 form a low-pass RC filter, which attenuates the high-frequency components of noise picked up by the feedback divider. Furthermore, the filter capacitor together with stray capacitance form a capacitive divider, which attenuates the noise on the feedback node.

This solution suffers from several deficiencies. Due to the integrating effect of the RC filter, the magnitude of the ripple voltage component will be reduced. The reduced ripple might be insufficient to ensure jitter-free switching, especially if the unfiltered value of the ripple was already small. Secondly, the RC filter introduces a phase shift into the feedback voltage. This phase shift might reduce the stability margin of the converter, and the converter might become unstable as a result.

SUMMARY OF THE INVENTION

A switched noise filter circuit for a DC-DC converter is presented which overcomes the problems noted above.

The present noise filter circuit is for use with DC-DC converters which use the instantaneous output voltage to regulate the output voltage. The DC-DC converter includes a switching control circuit which cycles the switching element on and off to maintain a desired output voltage, with each switching cycle comprising an "on" time interval T_{on} and an "off" time interval T_{off} . The switching control circuit typically includes a resistive divider connected to produce a feedback voltage V_{fb} at a feedback node (with V_{fb} representative of the instantaneous output voltage); a filter capacitance connected between the feedback node and the converter's local ground, and a comparator which

receives V_{fb} at its first input and a voltage V_2 which varies with a fixed reference voltage V_{ref} at its second input. The switching control circuit is arranged such that at least one of each switching cycle's "on" and "off" time intervals is terminated when V_{fb} crosses V_2 due to the natural discharge of the filter capacitance through the resistive divider. Such a time interval is referred to herein as a "modulated" time interval.

The switching control circuit also includes a switched noise filter circuit arranged to apply an offset voltage to V_{fb} during at least one of the "on" and "off" time intervals, with the offset voltage disconnected from the feedback voltage by the beginning of the immediate modulated time interval or shortly thereafter, so that V_{fb} is allowed to gradually decay toward V_2 . When the offset voltage is properly applied, the effect of extraneous electromagnetic noise coupled into V_{fb} is reduced.

The invention can be used with a wide variety of DC-DC converter configurations, including those employing constant-on-time valley-voltage control, constant-off-time peak-voltage control, constant-frequency peak-voltage or valley-voltage control, hysteretic control, or V_{square} control.

Further features and advantages of the invention will be apparent to those skilled in the art from the following detailed description, taken together with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of a known DC-DC converter.

FIG. 2 is a schematic diagram of a switched noise filter circuit per the present invention employed in a DC-DC converter which uses constant-on-time valley-voltage control.

FIG. 3 is a timing diagram which illustrates the operation of the DC-DC converter shown in FIG. 2.

FIG. 4 is a schematic diagram of an alternative embodiment of a switched noise filter circuit per the present invention employed in a DC-DC converter which uses constant-on valley-voltage control.

FIG. 5 is a timing diagram which illustrates the operation of the DC-DC converter shown in FIG. 4.

FIG. 6 is a schematic diagram of another alternative embodiment of a switched noise filter circuit per the present invention employed in a DC-DC converter which uses constant-on valley-voltage control.

FIG. 7 is a timing diagram which illustrates the operation of the DC-DC converter shown in FIG. 6.

FIG. 8 is a schematic diagram of a switched noise filter circuit per the present invention employed in a DC-DC converter which uses hysteretic control.

FIG. 9 is a timing diagram which illustrates the operation of the DC-DC converter shown in FIG. 8.

FIG. 10 is a schematic diagram of a switched noise filter circuit per the present invention employed in a DC-DC converter which uses constant-off-time peak-voltage control.

FIG. 11 is a timing diagram which illustrates the operation of the DC-DC converter shown in FIG. 10.

FIG. 12a is a schematic diagram of an alternative embodiment of a switched noise filter circuit per the present invention employed in a DC-DC converter which uses constant-off-time peak-voltage control.

FIG. 12b is a schematic diagram of another alternative embodiment of a switched noise filter circuit per the present invention employed in a DC-DC converter which uses constant-off-time peak-voltage control.

FIG. 13 is a schematic diagram of a switched noise filter circuit per the present invention employed in a DC-

DC converter which uses constant-frequency valley-voltage control.

FIG. 14 is a timing diagram which illustrates the operation of the DC-DC converter shown in FIG. 13.

5 FIG. 15a is a schematic diagram of an alternative embodiment of a switched noise filter circuit per the present invention employed in a DC-DC converter which uses constant-frequency valley-voltage control.

10 FIG. 15b is a schematic diagram of another alternative embodiment of a switched noise filter circuit per the present invention employed in a DC-DC converter which uses constant-frequency valley-voltage control.

15 FIG. 16 is a schematic diagram of a switched noise filter circuit per the present invention employed in a DC-DC converter which uses Vsquare control.

FIG. 17 is a timing diagram which illustrates the operation of the DC-DC converter shown in FIG. 16.

20 FIG. 18a is a schematic diagram of an alternative embodiment of a switched noise filter circuit per the present invention employed in a DC-DC converter which uses Vsquare control.

25 FIG. 18b is a schematic diagram of another alternative embodiment of a switched noise filter circuit per the present invention employed in a DC-DC converter which uses Vsquare control.

DETAILED DESCRIPTION OF THE INVENTION

30 The present switched noise filter circuit reduces the adverse effect of electromagnetic noise on DC-DC converters which employ the instantaneous output voltage to regulate the output voltage. As such, it is useful with many different DC-DC converter configurations, including those employing constant-on-time valley-voltage control, constant-off-time peak-voltage control, constant-frequency peak-voltage or valley-voltage control, hysteretic control,

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or Vsquare control.

An embodiment of the present invention as it might be used with a DC-DC converter which uses constant-on-time valley-voltage control is shown in FIG. 2. As in FIG. 1, a switching element 10 is connected between input voltage V_{in} and node 12, and inductor L is connected between node 12 and output terminal 14 at which regulated output voltage V_{out} is provided. Inductor current I_L feeds a load network comprising capacitance C_{out} and load 16. The switching of element 10 is controlled by a switching control circuit 40, which cycles element 10 on and off once per switching cycle. Feedback voltage V_{fb} is produced at feedback node 42, typically using a resistive divider $R1/R2$ connected between output terminal 14 and the converter's local ground; filter capacitor C_f is connected between feedback node 42 and ground. Feedback voltage V_{fb} is connected to one of the inputs of comparator A1, and a voltage $V2$ which varies with reference voltage V_{ref} (here, V_{ref} itself) is applied at the comparator's other input. When V_{fb} drops below and/or rises above V_{ref} , the comparator changes state. A monostable multivibrator (MMV) 44 is triggered when V_{fb} falls below V_{ref} , which toggles the MMV's Q output and closes switching element 10. Note that for the converter-types discussed herein, voltage $V2$ is equal to V_{ref} , except for those employing Vsquare control, in which case $V2$ is equal to the output of the voltage error amplifier (discussed below).

The time interval when switching element 10 is closed is referred to herein as "on" time interval T_{on} , and the interval during which switching element 10 is closed is referred to as "off" time interval T_{off} . Each of the converter's "switching cycles" includes an "on" time interval followed by an "off" time interval. The switching control circuit 40 for this embodiment, and for all converter configurations for which the present invention is applicable, is arranged such that at least one of each

switching cycle's "on" and "off" time intervals is terminated when V_{fb} crosses V_2 due to the natural discharge of the filter capacitance through the resistive divider. Such a time interval is referred to herein as a "modulated" time interval.

For the embodiment shown in FIG. 2, when triggered, MMV 44 toggles its Q output and closes switching element 10 for a fixed time interval controlled by the MMV, which establishes the switching cycle's "on" time interval T_{on} . This causes V_{out} and V_{fb} to increase, with V_{fb} eventually increasing above V_{ref} . At the end of the fixed time interval, the MMV's Q output goes low. V_{fb} will start to decay toward V_{ref} due to the natural discharge of filter capacitor C_f through the R1/R2 divider. The MMV's Q output remains low ("off" time interval T_{off}) until V_{fb} again falls below V_{ref} and triggers the MMV. This converter regulation technique is referred to as constant-on-time valley-voltage control.

However, electromagnetic noise coupled into feedback voltage V_{fb} , via mutual inductance or stray capacitance coupled from an adjacent converter, for example, can lead to jitter, undesirable frequency synchronization, premature switching, or other malfunctions. This problem is mitigated with the use of a switched noise filter circuit which is incorporated into switching control circuit 40. The switched noise filter circuit is arranged to apply an offset voltage V_{os} to feedback voltage V_{fb} during at least one of the switching cycle's "on" and "off" time intervals, and then for this embodiment - and for all converter configurations for which the present invention is applicable - disconnecting the offset voltage source from feedback node 42 by the beginning of the immediate modulated interval or shortly thereafter, so that V_{fb} is allowed to gradually decay toward V_2 due to the natural discharge of filter capacitor C_f through the resistive

divider. By so doing, the adverse effects related to the coupling of extraneous electromagnetic noise into the feedback voltage are reduced. When the offset voltage is applied during the modulated interval, the "immediate modulated interval" refers to the current time interval. When the offset voltage is applied during the time interval prior to the modulated interval, the "immediate modulated interval" refers to the subsequent time interval. In the exemplary embodiment shown in FIG. 2, switched noise filter circuit 46 comprises a voltage source 48 which produces an offset voltage V_{os} at its output, and an offset voltage switch 50 connected between the output of voltage source 48 and V_{fb} . Offset voltage V_{os} is preferably referred to reference voltage V_{ref} . Offset voltage switch 50 is controlled by the Q output of MMV 44, such that it is closed whenever switching element 10 is closed. In this way, V_{os} is added to feedback voltage V_{fb} during the switching cycle's "on" time interval, and is disconnected from V_{fb} at the beginning of and throughout the switching cycle's "off" time interval. When V_{os} is disconnected - i.e., during T_{off} - V_{fb} is allowed to gradually decay toward V_2 due to the natural discharge of filter capacitor C_f through the resistive divider.

When so arranged, a timing diagram such as that shown in FIG. 3 is obtained, which depicts V_{out} , V_{ref} , and V_{fb} over several switching cycles. Offset voltage V_{os} is added to V_{fb} during T_{on} , pulling feedback node 42 up to a fixed voltage ($V_{ref} + V_{os} = 1V + 40mV = 1.04V$ in this example); this increases the voltage difference between V_{fb} and V_{ref} and thereby increases the noise margin. With an increased noise margin, the effect of noise picked up at feedback voltage node 42 is reduced.

As noted above, the offset voltage must be disconnected from feedback node 42 by the beginning of the immediate modulated interval or shortly thereafter. In this

case, T_{off} is the immediate modulated time interval. V_{os} is applied for the entire duration of T_{on} , and is disconnected from feedback node 42 by the beginning of subsequent interval T_{off} , allowing V_{fb} to gradually decay toward V_2 due to the natural discharge of filter capacitor C_f through the resistive divider.

In DC-DC converters which employ constant on-time control (either valley-voltage or V_{square}), the offset voltage should be applied during T_{on} , or for a brief period at the very beginning of T_{off} . In converters with constant off-time control (either peak-voltage or V_{square}), the offset voltage should be applied during T_{off} , or for a brief period at the very beginning of T_{on} . In converters with constant-frequency control, the offset voltage should be applied after V_{fb} has decayed to V_2 , and preferably be disconnected when the clock pulse appears (although it could be disconnected earlier, too). In converters with hysteretic control (including the hysteretic version of V_{square}), both T_{on} and T_{off} are terminated when V_{fb} decays to V_2 ; here, the offset voltage is bidirectional and must be applied right after the threshold crossings, and preferably for a short interval only.

Note that it is not necessary that V_{os} be applied for the entire duration of a time interval - it need only be applied for a portion of a time interval. V_{os} should be present before the ripple voltage component of V_{out} would initiate a switching instant, and is preferably applied at the beginning of a time interval - so that the protection provided by the switched noise filter circuit against noise-induced switching extends to the better part of the interval.

When the switched noise filter circuit is active during a time interval having a duration which is not fixed with, for example, a MMV, the use of the present switched noise filter circuit may alter the duration of the time

interval - as it shifts the valley or peak of the output voltage slightly down or up. However, this shift is typically less than 1% of the output voltage, which is generally acceptable.

5 Though the RC filter formed by C_f , R_1 and R_2 still tend to reduce the magnitude of the ripple voltage present in V_{fb} , this is compensated for by the application of offset voltage V_{os} .

10 Another possible embodiment of the present invention as it might be used with a DC-DC converter which uses constant-on-time valley-voltage control is shown in FIG. 4. This configuration is similar to that shown in FIG. 2, except that the switched noise filter circuit 46 in switching control circuit 40 comprises a current source 60.
15 Current source 60 is controlled by the Q output of MMV 44, such that it is activated and produces a charging current I_c whenever switching element 10 is closed, and is deactivated when switching element 10 is open; note that, as used herein, "de-activating" the current source is the
20 equivalent of "disconnecting" the offset voltage. When activated, current source 60 charges filter capacitor C_f with charging current I_c . This causes feedback voltage V_{fb} to be increased during the switching cycle's "on" time interval.

25 When so arranged, a timing diagram such as that shown in FIG. 5 is obtained, which depicts V_{out} , $V_{ref}(=V_2)$, and V_{fb} over several switching cycles. Charging current I_c is supplied to feedback node 42 and charges C_f during T_{on} , increasing the magnitude of feedback voltage V_{fb} ; this
30 increases the voltage difference between V_{fb} and V_{ref} and thereby increases the noise margin and reduces the effect of noise picked up at feedback voltage node 42. As required by the invention, charging current I_c is reduced to zero by the beginning of the immediate modulated interval or
35 shortly thereafter. In this case, T_{off} is the immediate

modulated interval. I_c is applied for the entire duration of T_{on} , and is reduced to zero at the beginning of subsequent interval T_{off} , allowing V_{fb} to gradually decay toward V_2 due to the natural discharge of filter capacitor C_f through the resistive divider.

Note that charging current I_c may be a constant current, a varying current, or a current pulse; it is only necessary that the charging current provide a net charge of the proper polarity by the end of the switching cycle time interval during which current source 60 is activated.

In FIGS. 2-5 above, an offset voltage is applied to feedback node 42 during "on" time interval T_{on} . The offset voltage can alternatively be applied during the "off" time interval T_{off} . This is illustrated in FIG. 6, which depicts an embodiment of the present invention as it might be used with a DC-DC converter which uses constant-on-time valley-voltage control, with the offset voltage applied during the "off" time. This configuration is similar to that shown in FIG. 2, except that here the switched noise filter circuit 46 in switching control circuit 40 comprises a voltage source 70 which produces an offset voltage V_{os} at its output, an offset voltage switch 72 connected between the output of voltage source 70 and V_{fb} , and a second MMV 74.

Offset voltage switch 72 is controlled by the Q output of MMV 74, which is triggered by the \bar{Q} output of MMV 44. When so arranged, MMV 74 is triggered when switching element 10 is opened - i.e., at the beginning of T_{off} - and closes offset switch 72 for a fixed time interval established by MMV 74. In this way, switch 72 is closed and V_{os} is added to feedback voltage V_{fb} for a fixed time interval during T_{off} , and is open throughout the switching cycle's "on" time interval.

When so arranged, a timing diagram such as that shown in FIG. 7 is obtained, which depicts V_{out} , $V_{ref}(=V_2)$, and V_{fb}

over several switching cycles. Offset voltage V_{os} is added to V_{fb} during T_{off} , pulling feedback node 42 up (to a voltage $V_{ref} + V_{os} = 1V + 40mV = 1.04V$ in this example); this increases the voltage difference between V_{fb} and V_{ref} and thereby
 5 increases the noise margin. With an increased noise margin, the effect of noise picked up at feedback voltage node 42 is reduced.

As noted above, the offset voltage must be disconnected from feedback node 42 by the beginning of the
 10 immediate modulated interval or shortly thereafter. In this case, V_{os} is applied during T_{off} , and T_{off} is also the immediate modulated interval. Therefore, it is necessary that V_{os} be applied for a short interval T at the beginning of T_{off} , with $T \ll T_{off}$ (preferably 10% or less of T_{off}) -
 15 such that the offset voltage decays to zero or near-zero by the end of T_{off} . This is necessary to ensure that the effect of the offset voltage on the normal pulse-width modulation (PWM) process - and on the nominal converter operation itself - is negligible. Thus, when applying V_{os} during the
 20 "off" interval, the time constant $C_f(R1 \parallel R2)$ and the duration and termination of the V_{os} pulse, should be adjusted such that V_{os} is zero or near-zero by the end of the interval during which it is applied - which in this case is "off" interval T_{off} . If V_{os} does not decay to close to zero during
 25 the expected time, V_{out} will be adjusted such that the sum of the remaining offset voltage and V_{fb} equal V_{ref} , thereby causing V_{out} to deviate from the desired value.

The voltage source 70 and offset voltage switch 72 might alternatively be implemented with a current source
 30 (not shown), which is activated to charge filter capacitor C_f with a charging current for at least a portion of "off" time interval T_{off} , and is de-activated throughout the switching cycle's "on" time interval.

The present switched noise filter circuit can also be
 35 employed with a DC-DC converter using hysteretic control.

Such a converter is shown in FIG. 8. In this case, the switched noise filter circuit is arranged to subtract an offset voltage V_{os1} from feedback voltage V_{fb} during the switching cycle's "on" time interval, and to add an offset voltage V_{os2} to feedback voltage V_{fb} during the switching cycle's "off" time interval, with both V_{os1} and V_{os2} reduced to zero by the end of the time intervals during which they are applied.

In the exemplary embodiment shown in FIG. 8, comparator A1 has an associated hysteresis voltage V_{hyst} . This results in an upper threshold voltage $V_{uth} = V_{ref} + (V_{hyst}/2)$, and a lower threshold voltage $V_{lth} = V_{ref} - (V_{hyst}/2)$. The output of A1 is connected directly to switching element 10. In operation, V_{fb} needs to fall below V_{lth} to turn on switching element 10, and V_{fb} needs to rise above V_{uth} to turn off switching element 10, thereby providing hysteretic control.

Switched noise filter circuit 46 comprises a first voltage source 80 which produces offset voltage V_{os1} at its output, a first offset voltage switch 82 connected between the output of voltage source 80 and V_{fb} , a second voltage source 84 which produces offset voltage V_{os2} at its output, a second offset voltage switch 86 connected between the output of voltage source 84 and V_{fb} , and first and second MMVs 88 and 90. Offset voltages V_{os1} and V_{os2} are preferably referred to reference voltage V_{ref} .

Offset voltage switch 82 is controlled by the Q output of MMV 88, which is triggered to toggle its Q output for a fixed time interval at the start of "on" time interval T_{on} . Similarly, offset voltage switch 86 is controlled by the Q output of a MMV 90, which is triggered to toggle its Q output for a fixed time interval at the start of "off" time interval T_{off} . When so arranged, V_{os1} is subtracted from feedback voltage V_{fb} at the beginning of T_{on} , and V_{os2} is

added to feedback voltage V_{fb} at the beginning of T_{off} .

The resulting waveforms are shown in FIG. 9. As noted above, the offset voltage must be disconnected from feedback node 42 by the beginning of the immediate modulated interval or shortly thereafter. In this case, an offset voltage is applied during T_{on} and T_{off} , and both T_{on} and T_{off} are terminated when V_{fb} crosses V_2 ; thus, both T_{on} and T_{off} are immediate modulated intervals. Therefore, it is necessary that V_{os1} be applied for a short interval T_1 at the beginning of T_{on} , with $T_1 \ll T_{off}$, and V_{os2} be applied for a short interval T_2 at the beginning of T_{off} , with $T_2 \ll T_{off}$, such that the offset voltages decay to zero or near-zero by the end of their respective intervals.

The present switched noise filter circuit can also be employed with a DC-DC converter using constant-off-time peak-voltage control; such a converter is shown in FIG. 10. Here, feedback voltage V_{fb} is connected to the non-inverting input of A1, reference voltage $V_{ref}(=V_2)$ is connected to A1's inverting input, and A1's output is connected to trigger a MMV 100 when V_{fb} rises above V_{ref} . The \bar{Q} output of MMV 100 is connected to switching element 10, so that switching element 10 is opened for a predetermined time interval set by MMV 100 when V_{fb} rises above V_{ref} - thereby providing constant-off-time peak-voltage control.

In this embodiment, switched noise filter circuit 46 comprises a voltage source 102 which produces an offset voltage V_{os} at its output, and an offset voltage switch 104 connected between the output of voltage source 102 and V_{fb} . Offset voltage switch 104 is controlled by the Q output of MMV 100, such that it is closed whenever switching element 10 is open. In this way, V_{os} is subtracted from feedback voltage V_{fb} during the switching cycle's "off" time interval, and is disconnected from feedback node 42 during the switching cycle's "on" time interval.

When so arranged, a timing diagram such as that shown in FIG. 11 is obtained. Offset voltage V_{os} is subtracted from V_{fb} during T_{off} , pulling feedback node 42 down to a fixed voltage ($V_{ref} - V_{os} = 3V - 30mV = 2.97V$ in this example); this increases the voltage difference between V_{fb} and V_{ref} and thereby increases the noise margin. With an increased noise margin, the effect of noise picked up at feedback voltage node 42 is reduced.

Again, the offset voltage must be disconnected from feedback node 42 by the beginning of the immediate modulated interval. In this case, T_{on} is the modulated interval. V_{os} is applied for the entire duration of T_{off} , and is disconnected from feedback node 42 by the beginning of subsequent interval T_{on} , allowing V_{fb} to gradually decay toward V_2 due to the natural discharge of filter capacitor C_f through the resistive divider.

Alternative embodiments of DC-DC converters which use constant-off-time peak-voltage control and employ the present switched noise filter circuit are shown in FIGS. 12a and 12b. The configuration shown in FIG. 12a is similar to that shown in FIG. 4: switched noise filter circuit 46 comprises a current source 110 which is controlled by the Q output of MMV 100, such that it is activated and provides a discharging current I_c whenever switching element 10 is open, and is de-activated when switching element 10 is closed. When activated during the "off" time interval, current source 110 discharges filter capacitor C_f with discharging current I_c . This causes feedback voltage V_{fb} to be decreased during the switching cycle's "off" time interval, such that an improved noise margin is obtained.

In FIG. 12b, a fixed offset voltage is subtracted from the feedback voltage at the beginning of the "on" time interval. This configuration is similar to that shown in FIG. 6: switched noise filter circuit 46 comprises a voltage source 120 which produces an offset voltage V_{os} at

its output, an offset voltage switch 122 connected between the output of voltage source 120 and V_{fb} , and a second MMV 124. Offset voltage switch 122 is controlled by the Q output of MMV 124, which is triggered by the \bar{Q} output of MMV 100. When so arranged, MMV 124 is triggered when switching element 10 is closed - i.e., at the beginning of T_{on} - and closes offset switch 122 for a fixed time interval controlled by MMV 124. In this way, switch 122 is closed and V_{os} is subtracted from feedback voltage V_{fb} for a fixed time interval during T_{on} , and is open throughout the switching cycle's "off" time interval.

Offset voltage V_{os} should be applied for a short interval T at the beginning of T_{on} , with $T \ll T_{on}$ (preferably 10% or less of T_{off}) - such that the offset voltage decays to zero or near-zero by the end of T_{on} . This is necessary to ensure that the effect of the offset voltage on the normal PWM process, and on the nominal converter operation itself, is negligible.

The invention is also applicable to DC-DC converters using constant-frequency peak-voltage or valley-voltage control. An exemplary embodiment of a DC-DC converter using constant-frequency valley-voltage control which employs the present switched noise filter circuit is shown in FIG. 13. Here, the output of comparator A1 is connected to the set input of an S-R latch 130, with the latch's reset input connected to a periodic clock signal 132. The latch's Q output controls switching element 10. When V_{fb} falls below $V_{ref}(=V_2)$, the output of A1 toggles and sets the latch's Q output, causing switching element 10 to be closed. Switching element 10 remains closed until the next tick of periodic clock signal 132, which resets the latch.

In this embodiment, switched noise filter circuit 46 comprises a voltage source 134 which produces an offset voltage V_{os} at its output, and an offset voltage switch 136

connected between the output of voltage source 134 and V_{fb} . Offset voltage switch 136 is controlled by the Q output of S-R latch 130 such that it is closed whenever switching element 10 is closed. In this way, V_{os} is added to feedback voltage V_{fb} during the switching cycle's "on" time interval, and is zero during the switching cycle's "off" time interval.

When so arranged, a timing diagram such as that shown in FIG. 14 is obtained. Offset voltage V_{os} is added to V_{fb} during T_{on} , pulling feedback node 42 up to a fixed voltage ($V_{ref} + V_{os} = 3V + 30mV = 3.03V$ in this example); this increases the voltage difference between V_{fb} and V_{ref} and thereby increases the noise margin. With an increased noise margin, the effect of noise picked up at feedback voltage node 42 is reduced. In this case, T_{off} is the immediate modulated interval. V_{os} is applied for the entire duration of T_{on} , and is disconnected from feedback node 42 at the beginning of subsequent interval T_{off} , allowing V_{fb} to gradually decay toward V_2 due to the natural discharge of filter capacitor C_f through the resistive divider.

Alternative embodiments of DC-DC converters which use constant-frequency valley-voltage control and employ the present switched noise filter circuit are shown in FIGs. 15a and 15b. The configuration shown in FIG. 15a is similar to that shown in FIGs. 4 and 12a: switched noise filter circuit 46 comprises a current source 140 which is controlled by the Q output of latch 130, such that it is activated and produces a charging current I_c whenever switching element 10 is closed, and is de-activated when switching element 10 is open. When activated during the "on" time interval, current source 140 charges filter capacitor C_f with charging current I_c . This causes feedback voltage V_{fb} to be increased during the switching cycle's "on" time interval such that an improved noise margin is obtained.

In FIG. 15b, a fixed offset voltage is added to the feedback voltage at the beginning of the "off" time interval. The configuration shown in FIG. 15b is similar to that shown in FIGS. 6 and 12b: switched noise filter circuit 46 comprises a voltage source 150 which produces an offset voltage V_{os} at its output, an offset voltage switch 152 connected between the output of voltage source 150 and V_{fb} , and a MMV 154. Offset voltage switch 152 is controlled by the Q output of MMV 154, which is triggered by the \bar{Q} output of latch 130. When so arranged, MMV 154 is triggered when switching element 10 is opened - i.e., at the beginning of T_{off} - and closes offset switch 152 for a fixed time interval controlled by MMV 154. In this way, switch 152 is closed and V_{os} is added to feedback voltage V_{fb} for a fixed time interval during T_{off} , and is open throughout the switching cycle's "on" time interval. Offset voltage V_{os} should be applied for a short interval T at the beginning of T_{off} , with $T \ll T_{off}$ (preferably 10% or less of T_{off}) - such that the offset voltage decays to zero or near-zero by the end of T_{off} .

Though not shown, the present switched noise filter circuit may also be employed with DC-DC converters using constant-frequency peak-voltage control.

The invention is also applicable to DC-DC converters using Vsquare control. An exemplary embodiment of a DC-DC converter using Vsquare control which employs the present switched noise filter circuit is shown in FIG. 16. Here, feedback voltage V_{fb} is connected to the non-inverting input of A1, a voltage $V_{error}(=V_2)$ which varies with reference voltage V_{ref} is connected to A1's inverting input, and A1's output is connected to trigger a MMV 160 when V_{fb} rises above V_{error} . The \bar{Q} output of MMV 160 is connected to switching element 10, so that switching element 10 is opened for a predetermined time interval set by MMV 160

when V_{fb} rises above V_{error} .

V_{error} is produced by a voltage error amplifier A2, which is typically connected to V_{ref} at its non-inverting input, to a voltage representative of V_{out} at its inverting
 5 input, and which has an RC feedback network connected between its output and inverting input, such that V_{error} varies with difference between V_{ref} and V_{out} . When so arranged, the DC-DC converter provides Vsquare control.

In this embodiment, switched noise filter circuit 46
 10 comprises a voltage source 162 which produces an offset voltage V_{os} at its output, and an offset voltage switch 164 connected between the output of voltage source 162 and V_{fb} . Offset voltage V_{os} is preferably referred to error voltage V_{error} . Offset voltage switch 164 is controlled by the Q
 15 output of MMV 160, such that it is closed whenever switching element 10 is open. In this way, V_{os} is subtracted from feedback voltage V_{fb} during the switching cycle's "off" time interval, and is zero during the switching cycle's "on" time interval.

20 When so arranged, a timing diagram such as that shown in FIG. 17 is obtained. Offset voltage V_{os} is subtracted from V_{fb} during T_{off} , pulling feedback node 42 down; this increases the voltage difference between V_{fb} and V_{ref} (and V_{error}) and thereby increases the noise margin. With an
 25 increased noise margin, the effect of noise picked up at feedback voltage node 42 is reduced.

In this case, T_{on} is the immediate modulated interval. V_{os} is applied for the entire duration of T_{on} , and is disconnected from feedback node 42 at the beginning of
 30 subsequent interval T_{off} , allowing V_{fb} to gradually decay toward V_2 due to the natural discharge of filter capacitor C_f through the resistive divider.

Alternative embodiments of DC-DC converters which use Vsquare control and employ the present switched noise
 35 filter circuit are shown in FIGs. 18a and 18b. The

configuration shown in FIG. 18a is similar to that shown in FIGs. 4, 12a, and 15a: switched noise filter circuit 46 comprises a current source 170 which is controlled by the Q output of MMV 160, such that it is activated and produces a
 5 discharging current I_c whenever switching element 10 is open, and is de-activated when switching element 10 is closed. When activated during the "off" time interval, current source 170 discharges filter capacitor C_f with discharging current I_c . This causes feedback voltage V_{fb} to
 10 be decreased during the switching cycle's "off" time interval, such that an improved noise margin is obtained.

In FIG. 18b, a fixed offset voltage is subtracted from the feedback voltage at the beginning of the "on" time interval. This configuration is similar to that shown in
 15 FIGs. 6, 12b and 15b: switched noise filter circuit 46 comprises a voltage source 180 which produces an offset voltage V_{os} at its output, an offset voltage switch 182 connected between the output of voltage source 180 and V_{fb} , and a MMV 184. Offset voltage switch 182 is controlled by
 20 the Q output of MMV 184, which is triggered by the \bar{Q} output of MMV 160. When so arranged, MMV 184 is triggered when switching element 10 is closed - i.e., at the beginning of T_{on} , and closes offset switch 182 for a fixed time interval controlled by MMV 184. In this way, switch 182 is closed
 25 and V_{os} is subtracted from feedback voltage V_{fb} for a fixed time interval during T_{on} , and is open throughout the switching cycle's "off" time interval.

V_{os} should be applied for a short interval T at the beginning of T_{on} , with $T \ll T_{on}$ (preferably 10% or less of
 30 T_{on}) - such that the offset voltage decays to zero or near-zero by the end of T_{on} - to ensure that the effect of the offset voltage on the normal PWM process, and on the nominal converter operation itself, is negligible.

Note that the embodiments shown in FIGs. 2-18 are

merely exemplary. As previously noted, the present switched noise filter circuit can be employed with any DC-DC converter which uses the instantaneous output voltage to establish the duty ratio required for maintaining the output voltage, including those employing constant-on-time valley-voltage control, constant-off-time peak-voltage control, constant-frequency peak-voltage or valley-voltage control, hysteretic control, or Vsquare control.

Also note that, though each of the illustrated embodiments depicts a single switching element connected in series with a rectifier diode D, the invention is equally applicable to converters for which rectifier diode D is replaced with a second switching element, which is turned on when switching element 10 is turned off (and vice versa), respectively, to provide synchronous rectification.

While particular embodiments of the invention have been shown and described, numerous variations and alternate embodiments will occur to those skilled in the art. Accordingly, it is intended that the invention be limited only in terms of the appended claims.